SECRET

Technical Report

Bureau No. 12 Mercury Rectifiers NTO MEP

Subject: Controlled Rectifiers Under Short Circuit Conditions

12.805

No. of Sheets of Text: 11 Author

No. of Sheets of Supplements: 10

No. of Photographs: Date: 23 Nov 1948

Summary of Contents

Investigates the stationary processes of a controlled rectifier under short circuit conditions using the bridge system and various angles of ignition. Examines processes both when the short circuit is at the rectifier and when it is beyond the rectifier filter choke.

Chief of NTO MEP in Germany Chief of Bureau No. 12

Signed: —— Checked: —— Author: —— Accepted by Project Leader: ——

Table of Contents

Short-Circuited Controlled Rectifier Under Short-Circuit Conditions

SECRET SECRET

Controlled Rectifier under Short-Circuit Conditions

1) Current during prolonged short circuit.

The projected application of high voltage direct current for long-distance transmission raises afresh the question of the behavior of rectifiers when short circuited. The three-phase full wave or bridge connection is preferable for this purpose. The behavior of this connection on short circuit may be treated in a general manner utilizing the results of previous experiments on various circuits. (See Footnote 1 of original)

Treatment of the short circuit behavior of rectifiers has shown that apart from the particular circuit differences, a distinction must be made on the one hand between long and intermittent short circuits and, on the other hand, between the kind and position of the current-limiting inductances and the location of the short circuit. The natural inductance and ohmic resistance of the transformer or the additional line or anode chokes may be the decisive factor for the limiting of the short-circuit. The short circuit can occur before or after the cathode chokes. We shall consider the case of pure inductive current limiting, since it can be taken as the predominant type for large installations, and the ohmic resistance produces a negligible additional decrease of the short-circuit current. We shall first discuss the short circuit ~~behind~~ after the cathode choke, viz. directly on the output terminals of the rectifier in which case the ohmic resistance of the cathode choke will also be neglected.

a) Short circuit ~~behind~~ After the cathode choke.

The ignition and quenching of individual ~~phases~~ anodes of a rectifier constitutes a periodic cycle of switching operations with the inductive current-limiting impedances preventing sudden increase in current. The individual anode currents follow the alternating short circuit currents, arising during short circuit of the anode terminals which conduct current simultaneously. ~~be shifted to the positive range in such a manner that the current~~ However, these anode currents are shifted in polarity

SECRET

so that the current is continuously positive, ~~pursues a course without discontinuity~~ beginning at zero and returning again to zero at the end of the period. Hence, the problem is to determine ~~find~~ variations in the anode currents ~~the current regions of the plates~~ in order to assemble piecemeal the anode ~~plate~~ current from the corresponding ~~appropriate~~ alternating short-circuit currents. The current variation ~~change~~ involves a knowledge of the ~~instant of~~ ignition and ~~of the instant of~~ extinction points of the anodes ~~plates~~. The ~~instant of~~ ignition point is determined by the control voltage, with a positive plate voltage required at the instant of ignition. Hence, the first item to determine is the ~~instant of~~ extinction point.

When the short circuit is beyond the cathode choke, the ~~instant of~~ extinction point must be such that the rectified voltage before the cathode choke has a mean value of zero. This condition leads in general to the statement that <u>the current duration lies symmetrically about the point at which the phase voltage passes through zero.</u> This will be first shown with an ~~one~~ example of the three-phase rectifier.

We proceed from the condition of the rectifier controlled to zero. Then it is obviously meaningless whether or not a short circuit exists, i.e. the current-voltage conditions ~~ratio~~ would not be affected by a short-circuit.

We see in the upper part of Fig. 1 ~~above~~ the secondary phase voltages U_{1-0}, U_{2-0}, U_{3-0}. The rectified voltage with a mean value of zero is underscored. In general, this condition is met with an ignition lag of $\alpha = \pi/2$ with respect to the ~~instant of~~ ignition point of the uncontrolled rectifier at $z = (\pi/2 - \pi/p)$. Here, p is the number of phases on the secondary. Hence, for a three-phase rectifier

$$z = \frac{\pi}{2} - \frac{\pi}{3} = \frac{\pi}{6}$$

The current duration under normal conditions is:

$$\beta = \frac{2\pi}{p}$$

Hence, for a three-phase rectifier:

$$\beta = \frac{2\pi}{3}$$

In an uncontrolled rectifier, the current interval is symmetrical about the peak value of the phase voltage when $\omega t = \frac{\pi}{2}$, i.e. it extends between $z = \frac{\pi}{2} - \frac{\pi}{p}$ (ignition) and $z = \frac{\pi}{2} + \frac{\pi}{p}$ (extinction).

SECRET

When the ~~i~~gnition lag $\alpha = \frac{\pi}{2}$, the current duration extends between $2 + \alpha = \frac{\pi}{2} - \frac{\pi}{p} + \frac{\pi}{2}$ and $2 + \alpha + \beta = \frac{\pi}{2} + \frac{\pi}{p} + \frac{\pi}{2}$, i.e. between $\pi - \frac{\pi}{p}$ and $\pi + \frac{\pi}{p}$ and thus lies symmetrically about the zero passage of the phase voltage.

Let us imagine that a rectifier controlled to zero is switched on. The ~~plates~~ anodes in turn carry current in a circuit which is closed ~~over~~ through the cathode choke and the phase voltage.

At the bottom of Fig. 1 we see the alternating short-circuit current of this connection for ~~Phase~~ Anode 1. It is small enough to be neglected when the cathode choke is large. The ~~plate~~ anode current ~~is a~~ comprises ~~section~~ part of this current ~~whose time which is~~ with a duration of $\frac{2\pi}{3}$, as is shown below. The ~~plate~~ anode currents border on each other but do not overlap.

If we now advance the ignition, the current flow ~~times~~ periods will overlap and in accordance with the rule given above, that the current flow time is symmetrical about $\omega t = \pi$, the extinction point is retarded as much as the ignition is advanced. Fig. 2 shows us the resulting rectified voltage before the cathode choke for the ignition lag $\alpha = 60°$ electrical, $\alpha = 30°$, and $\alpha = 0°$. ~~We see the~~ The anode currents are also shown on this graph. ~~regimes of the plates above, in the middle and below.~~

The zero passage of the first phase voltage, about which the current duration of the first anode is symmetrical, is shown in a dot-dash line in the diagram.

Above, on the left hand side, the rectified voltage is underscored for $\alpha = 60°$ elec. We see that this voltage runs in the middle between the successive phase voltages, whenever two ~~plates~~ anodes are simultaneously carrying current, and follows the phase voltage when only one ~~plate~~ anode is conducting current. The curve on the top right hand side of Fig. 2 holds good for the current ~~regime in the~~ conditions shown middle of the graph where two ~~plates~~ anodes carry current. The voltage thus runs into the middle of the two ~~plate~~ anode voltages. This is a short-circuit of the linked voltage of the transformer ~~namely~~ with the short-circuit point assuming ~~at~~ the mean voltage ~~as~~ opposite the star neutral point ~~(0)~~. Below we see the voltage and the current ~~regime~~ conditions for $\alpha = 0°$. Here, there are time intervals in which the three anodes carry current simultaneously and therefore the rectified voltage will be zero; the common short-circuit point, the cathode, takes the mean voltage of all three phase voltage, i.e. zero.

We see from Fig. 2 that in all three cases the condition that the mean rectified voltage is zero is fulfilled.

The anode current can be constructed from the corresponding alternating currents in accordance with the current graph. This is shown in Fig. 3. Above, we see the first phase voltage and also the alternating currents short-circuit between the points 1 and 2; 1, 2 and 3; and 1 and 3. These currents determine the anode current $i_{1k(30)}$, because the cathode choke prevents the passage of alternating currents. The index shows which points of the circuit diagram are to be considered short-circuited. The anode current follows the displaced sections of these alternating currents in such a manner that a continuous curve results. For example, we see that the current for $\alpha = 0°$ is made up of five sections, corresponding to the scheme in Fig. 2, bottom. In Fig. 3, top, the section of the alternating currents, which determines the current below is shown hatched. It is a matter of a sequence of switching operations with impedances presumed to be purely inductive and the compensation current is therefore constant.

Since the alternating currents merely flow from anode to anode the current through the cathode choke remains constant. In the time intervals when only one anode is carrying current, e.g. when $\alpha = 60°$, the anode current is equal to the cathode current.

The rise of cathode current with decreasing ignition lag can be seen from Fig. 3 and is plotted in Fig. 4.

The cathode current is shown with respect to the effective alternating short-circuit current when the points 1, 2 and 3 are short-circuited. This condition exists when the short-circuit voltage of the transformer is being measured.

When the rectifier is overcontrolled the ignition point could be shifted forward to $\omega t = 0°$ whereas for normal operation $\omega t = 30°$. This is also the case when the rectifier is uncontrolled. Then the ~~plate~~ anode current assumes the form of an alternating current completely displaced into the positive zone as is shown by a broken line in the lower part of Fig. 3.

The associated cathode current rises to the value $3\sqrt{2} = 4.24$, i.e. three times the peak value of the normal alternating short-circuit current.

For the three-phase rectifier with a large cathode choke it does not matter whether the current-limiting inductances are in the line ~~of~~ or on the primary, or secondary side.

Now that we have established the basic short-circuit conditions for a three-phase rectifier, we can pass to the bridge circuit which is important for high-voltage transmission. (See the bottom left hand diagram in Fig. 5.) This circuit can be regarded as two three-phase rectifiers in series in which the secondary transformer winding is considered divided into two identical parts (whose star neutral points) are connected.

It can thus be seen that in this circuit there are two three-phase rectifiers in series, so that this can also be designated as a double three-phase series connection.

If the current-limiting inductances had been inserted directly before the valves (") as ~~plate~~ anode chokes, we should have gotten the same current were form from each partial rectifier as was considered above for the three-phase rectifier. But if the current-limiting inductances lie in the line or on the primary or secondary sides, different current and voltage conditions result, due to the influence on both sides.

We again draw on the case of the rectifier controlled to zero. The upper part of Fig. 5 shows the rectified voltages. The voltage of the left hand system is shown in a solid line and that of the right hand system is shown in a broken line. The first is in agreement with that of the three-phase rectifier shown in the upper part of Fig. 1.

The second is that of a three-phase rectifier ~~for~~ with negative voltage opposite the star neutral point of the transformer.

The potential difference across the choke coil on short circuit is the difference of the voltages:

$$U_{4-5} - U_{4-0} - U_{6-0}$$

This voltage causes a current which is shown in the middle part of Fig. 5. The current through valve 1 is drawn as a heavy line. Due to the change of voltage in the other system, the current has two peaks.

If the ignition delay is now reduced and the ~~instant of~~ extinction point is delayed by the same amount, we obtain the voltages shown in Fig. 6. On top we see the current conditions for $\alpha = 75°$, and the voltages for the right and left system respectively. In this case, they will not yet exert any mutual effect. The voltages vary in the same way as in the three-phase rectifier, because whenever two valves of one system are carrying current, only one valve in the other system will be carrying current, on a phase voltage which is not as yet affected.

However, as soon as two valves each in both systems are carrying current, it will be affected. In the bottom diagram of Fig. 6 it is shown that the rectified voltage in both systems becomes zero in that case. This will take place when $\alpha < 60°$. The bottom diagram of Fig. 6 applies to $\alpha = 45°$. In each system there are sections which alternate between zero voltage and the voltages of either a single phase or algebraic sum of the phase voltages. We see that the zero condition for the mean voltage is met in all cases. At $\alpha = 30°$, four valves are constantly carrying current simultaneously, and the voltages are ~~at~~ constantly zero. Thus, up to $\alpha = 60°$, the valve current will coincide with that of the three-phase rectifier, as shown at the bottom of Fig. 7. While the behavior of the current in the three-phase rectifier can be observed down to $\alpha = 0°$ or even down to $\alpha = -30°$ the limit in this case is reached at $\alpha = 30°$. We shall consider the

SECRET

construction of the plate current at $\alpha = 45°$, shown by the current flow diagram of Fig. 6, center, in more detail. In this case, with valve 1 carrying current, the following combinations of successively current-carrying valves are to be noted:

ωt =	75° to 105°	-	1'3' & 1"2"	carry current
" =	105° to 135°	-	1'3' & 2"	" "
" =	135° to 165°	-	1'3' & 2"3"	" "
" =	165° to 195°	-	1' & 2"3"	" "
" =	195° to 225°	-	1'2' & 2"3"	" "
" =	225° to 255°	-	1'2' & 3"	" "
" =	255° to 285°	-	1'2' & 3"1"	" "

Five different alternating currents must be employed for constructing the ~~plate~~ anode current. They are shown in Fig. 7, top, next to the phase voltage U_{1-0}. The sections used for forming the ~~plate~~ anode current below are shown by the hatched lines.

The three alternating currents which occur with complete secondary short-circuit (Index K (123)) and those occurring with short-circuit between 1 and 2 or 1 and 3 (under K (12) or K(13)) are shown on top in heavy lines. On the basis of the above tabulation it can be decided which current is to be employed during the individual time intervals. It must be noted that, when both the system under consideration and the other system each contain two current-carrying valves, the transformer will also be completely short-circuited, ~~while~~ and currents $i_{1K(123)}$, $i_{2K(123)}$, and $i_{3K(123)}$ will flow exclusively in those valves which carry the current of only one phase. Thus, e.g., in the first range, with 1', 3' and 1", 2" carrying current, the current $-i_{3K(123)}$ will determine i'_3 and thus $-i_{3K(123)}$ determines i'_1. This latter current returns through 1'. It determines the first rise of the plate short-circuit current in Fig. 7, bottom. In the next section, only valve 2" is carrying current in the second system, thus the current will follow current $i_{1K(13)}$ ~~across~~ through valve 1, because 1' and 3' in the first system are carrying current. Valve 3" will then ignite and, as shown above, $i_{1K(123)}$ becomes the controlling factor for valve 1'. Subsequently, only valve 1' carries current in the first system, so that the current will be constant. The same considerations apply to the downward slope.

The greatest anode current is reached at $\alpha = 30°$; the current follows in succession $-i_{3K(123)}$, $+i_{1K(123)}$, and $-i_{2K(123)}$. The transformer is constantly short-circuited. ~~If we draw the cathode current~~ If we plot the cathode current obtained from Fig. 7 (which is equal to the anode current in the constant range), in Fig. 4, with respect to the effective alternating short-circuit current, the deviation from the characteristics of the three-phase rectifier becomes evident at $\alpha = 60°$. The current is lower and the curve ends at $\alpha = 30°$.

The question now is what will happen when the control is set to $\alpha < 30°$. If the control pulse is a positive peak of at least 30° width, superimposed on a negative bias voltage, the ignition will set itself to $\alpha = 30°$ or $\omega t = 60°$, even though the set ignition angle is associated with $\alpha < 30°$. However, an automatic ignition delay up to $\alpha = 30°$ will occur. If the grid voltage consists of positive pulses of a width less than 30° el., some of the anodes may miss during ignition. In practice, however, a wide ignition pulse can be expected in high-voltage DC transmission.

b) Short-circuit before the cathode choke.

In the case of short-circuit before the cathode choke, the rectified voltage is directly short-circuited. The only criterion for the shape of the anode current is the condition that the anode current must zero at the instant of ignition, return to zero from. The rule, that the current duration must be symmetrical about the zero passage of the phase voltage, is maintained, in order to fulfill the above condition. The current of the three-phase rectifier with decreasing ignition is shown at the bottom of Fig. 8. Its characteristic is determined by the alternating currents that are generated when the transformer is short-circuited in one phase against the neutral point ($i_{1K(10)}$), or in two phases against the neutral point

SECRET

($i_{1K(120)}$ and $i_{1K(130)}$), with only two possibilities existing for each phase. The single-phase short-circuit is 3/2 greater than the three-phase current $i_{1K(123)}$, but [redacted] in phase, while the two-phase short-circuit currents are $\sqrt{3}$ greater and are 30° ahead or behind.

The anode short-circuit current at $\alpha = 90°$ is formed by the 120° (elec.) peak of the single-phase short-circuit current as shown in Fig. 8, bottom. When the ignition delay is decreased, the current duration periods overlap, but no more than two anodes can carry current continuously. This condition occurs already at $\alpha = 30°$. The anode current is made up of parts of $i_{1K(120)}$ and $i_{1K(130)}$. At this point, the transformer is short-circuited in such a manner, that it no longer has any voltage, which might make earlier ignition of the plates possible, as long as the current-limiting inductances are mostly on the primary side and in the line. However, if most of the inductances are located on the secondary side, the anode branches are independent of each other, and the current conditions prevailing will be those of the short-circuited single phase rectifier, whose current behavior has been described by W. Schilling in "Die Gleichrichterschaltungen" (Rectifier circuits), page 14 ff.

In case of short-circuit before the cathode choke the current of the rectifier cannot be based on the current of the simple three-phase rectifier.

Fig. 9, bottom shows the current across a valve with decreasing ignition delay. Since it is, at any given instant, a short-circuit of the linked transformer voltage, no more than three valves can carry current simultaneously. This condition is reached already at $\alpha = 60°$. Then the transformer is completely short-circuited and no voltage is available for the ignition of other valves. The current duration has become 180° el. and the valve current consists of the half-wave of the short-circuit current $i_{1K(123)}$ with a mean value of $\sqrt{2}/\pi$ of the effective value $I_{1K(123)}$. At $\alpha = 75°$, however, the anode current consists of five different sections, according to

SECRET

the current graph schematically shown at the bottom. Either the currents $i_{1K(123)}$ or the currents $i_{1K(12)}$ or $i_{1K(13)}$ are predominant, depending on whether the entire transformer or only the linked voltages U_{1-2} or U_{1-3} are short-circuited. The individual sections are shown in Fig. 9, top. At $\alpha = 90^{o}$, the anode current consists of the connected peaks of the two short-circuit currents $i_{1K(12)}$ and $i_{1K(13)}$, according to the current conditions shown in the center of Fig. 9.

While the cathode current with cathode choke could be assumed to be a pure d.c., a rippling d.c. must now be expected. The d.c. results from the summation of the three anode currents of the system. The highest anode current is shown as a broken line in Fig. 8, bottom. Since the complete transformer short-circuit is reached already at $\alpha = 60^{o}$, it will again depend on the type of control voltage, whether individual anodes will stop firing at $\alpha < 60^{o}$ or whether the ignition angle remains at $\alpha = 60^{o}$.

Fig. 10 shows the characteristic of the cathode current as a function of ignition delay which stops abruptly at $\alpha = 60^{o}$. At $\alpha = 90^{o}$ the characteristic does not begin with zero but with a residual value according to the current course shown in Fig. 9, bottom. Thus, it would be possible also during short-circuit conditions to increase the ignition delay above $\alpha = 90^{o}$. However, in that case, the cathode current will contain gaps.

The characteristic of the three-phase rectifier without cathode choke, drawn in for purposes of comparison, shows considerably higher values, provided the transformer short-circuit is the same.

While different current conditions prevail in the three-phase rectifier without cathode choke, depending on whether the current-limiting inductances are on the primary side or in the line, or on the secondary side before the anodes, no such difference exists in a bridge circuit, since the controlling alternating currents apply in the case of short-circuit of the linked voltage. The comparison of the characteristics of Figs. 10 and 4 also shows that the short-circuit current

SECRET

values with and without cathode choke do not differ greatly; E.g., with an alternating short-circuit current $I_{1K(123)}$ which is ten times the rated secondary current of the transformer

$$I_{1K(123)} = 10 \times I_{1N}.$$

Then, there results the following ratio to the normal value for the cathode short-circuit current $I_{4K(60)}$ or $I_{4K(40)}$, because the rated cathode current is $I_{4N} = \sqrt{\frac{3}{2}}\, I_{1N}$ with the characteristic value

$$\frac{I_{4K}}{I_{1K(123)}} \approx 1.4:$$

$$\frac{I_{4K(60)}}{I_{4N}} = \frac{I_{4K(60)}}{I_{1K(123)}} \cdot \frac{I_{K(123)}}{I_{1N}} \cdot \frac{I_{1N}}{I_{4N}} \approx$$

$$1.4 \times 10 \times \frac{\sqrt{2}}{\sqrt{3}} = \underline{11.5}$$

If the ohmic voltage losses are included, this value will be reduced further.

Summarizing, it can be stated that the constant short-circuit current of the bridge circuit depends on the pre-set ignition delay. With short-circuit ~~behind~~ after the cathode choke, the final value is reached at $\alpha = 30°$, with short-circuit before the cathode choke it is reached at $\alpha = 60°$.

The ratio between short-circuit current and normal current is approximately 10% greater than the corresponding ratio for the transformer. Since, normally, high-voltage DC transmission will be carried out with fully controlled rectifiers in order to decrease the reactive power in the ~~3~~ three-phase supply line, it can be expected in practice that the ignition pulse will be located ~~before~~ from $\alpha = 30°$ up to $\alpha = 60°$. With wide ignition pulses, the same constant short-circuit currents will occur. If the ignition pulses are narrow, individual ~~plates~~ anodes will miss. This will be discussed in the subsequent treatise on surge short-circuit.

END